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(71) Applicant: **AMERICAN TELEPHONE AND TELEGRAPH COMPANY**
32 Avenue of the Americas
New York, NY 10013-2412 (US)

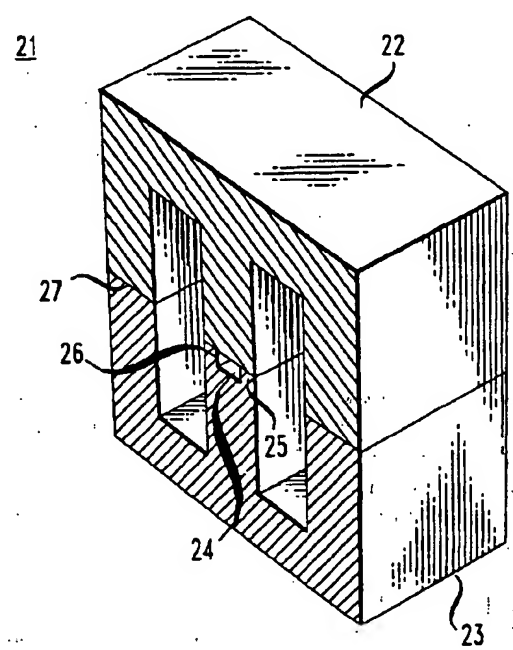
(72) Inventor: **Roy, Apurba**
1602 Amesbury Avenue
Rockwall, Texas 75087 (US)

(74) Representative: **Johnston, Kenneth Graham et al**
AT & T (UK) Ltd. 5 Mornington Road
Woodford Green Essex, IG8 OTU (GB)

(54) **Partial gap magnetic core apparatus.**

(57) Potted wire-wound loop-core structures are based on cores which include partial gapped inductors or transformers with their reduced dependence of inductance on current during operation. Total enclosure of gaps by encircling core material is both magnetic and physical, thereby avoiding fringing magnetic fields as well as joint failure due to differential expansion of potting material.

FIG. 2



EP 0 577 334 A2

Technical Field

The invention is concerned with apparatus dependent upon wire-wound core structures. Concerned cores, generally of ferrite or other soft magnetic material, are constituted of segments which, together, form a closed magnetic loop with at least one partially gapped joint thereby resulting in a structure known as a "partial gap" or "variable gap" core.

Description of the Prior Art

Wire-wound core devices serve a variety of functions. An important use is in power supplies in which they may serve as transformers to change voltage level as well as to isolate output from input circuitry. As inductors, they may take the form of choke coils for minimizing a.c. ripple and other forms of noise. They may serve, as well, for magnetic energy storage, e.g., in power supplies using flyback converter circuits.

A design limitation for such apparatus is the consequence of non-linear effects - ultimately of magnetic saturation - which results in pronounced dependence of inductance on current. Fall-off in inductance in the presence of currents with large d.c. components is a major consideration in the design of such apparatus.

Relevant prior art is discussed in conjunction with FIG. 1. This figure, on coordinates of inductance and direct current, each on a logarithmic scale, exhibits the general form of relationship of those two parameters for three types of structures. Curve 10, is descriptive of an ungapped loop core. Curve 11 shows the form of the relationship for a gapped structure - for a loop core having at least one gap extending across the entire core cross section. Curve 12 traces the general relationship for such a loop core which is "partially gapped" - for usual fabrication, in which concerned regions are the consequence of mating surfaces and in which the topography of one or both of such surfaces is such as to produce a mated joint which is partially gapped and partially continuous.

Curve 10, with its high initial inductance value plotted as peaking at near-zero current point 13, drops off rapidly to reach a low value at 14. The actual inductance value at 14, while too low to be of consequence for contemplated apparatus, is actually non-zero - is of a value approaching that of an air core structure. This steep drop-off in inductance is at too low a current to meet many apparatus requirements. For example, operating as a choke, it may fail to provide adequate smoothing at full contemplated output.

Curve 11 is based on a full gap structure otherwise structurally similar to that of curve 10. Presence of such a non-magnetic gap - e.g., of an "air" gap - since not magnetically saturable, results in near independence of inductance - in a constant or nearconstant inductance plateau at 15. The full gap structure is characterized by perseverance of significant inductance at higher currents, reaching a near-zero inductance value only at 16. However, the full gap structure is characterized, as well, by a reduced initial, inductance value 17. For many purposes, this initial low value of inductance is inadequate for intended use.

It is known that desired characteristics of gapped and ungapped core structures may, to some extent, be combined in a third type of structure. This latter sometimes referred to as "partial gap", "stepped gap" or "non-linear" core, takes the form of a core of reduced cross-section at some position. This is often realized by joinder of core segments of reduced cross-section to, together, result in core joint having a central contacting region surrounded by a peripheral gap.

Curve 12 traces inductance-current characteristics for a partial gap core with a gap depth approximating that of the structure of curve 11. Its initial or "near-zero current" inductance of value 18 approaches that of the ungapped core of curve 10. With increasing current, inductance drops to a plateau value of 19, to ultimately drop-off to a low, near-zero value 20, at a current level approaching that of drop-off for the gapped structure of curve 11.

Such partial gap "non-linear" structures have satisfied some performance requirements. Their use has resulted in initial inductance values approaching those of ungapped structures as well as retention of high-current inductance values characteristic of gapped structures. However, they retain certain characteristics of full gap structures which may be disadvantageous. From the performance standpoint, such stepped gap structures, like their full gap counterparts, also develop fringing magnetic fields at the gap. Coupling of such fringing fields with encircling windings result in decreased inductance per unit volume, in heating and, generally, in overall performance loss. The disadvantage is aggravated for planar devices and with increasing miniaturization. Structural variations may cause further problems. As an example, use of windings, e.g. helical windings, made of rectangular or oval cross-section conductors (with the large dimension in the radial direction), while useful in reducing d.c. electrical resistance, is effectively precluded due to larger field coupling and resulting increased heating and power loss.

A further disadvantage of the prior art non-linear structure, in manner similar to the full gap structure, takes its toll during fabrication as well as in use. Entry of potting compound into the exposed peripheral gap may cause physical failure. Curing or crystallization of the potting material may be attended by volume change to disrupt the joint. In use, joint failure may be caused by localized heating due to resistive losses in the windings and to electromagnetic losses in the core. Failure may be caused by differential thermal expansion within different regions of the invading pot-

ting material, or even by uniform expansion of potting material differing from that of contacting regions of the core. Even if physical joint failure does not occur, the differential thermal expansion of potting material in the gap may lead to an unpredictable or unwanted effective temperature coefficient of inductance for the device.

The foregoing is treated in a number of articles and texts. See, for example, Soft Ferrites Properties and Applications, E. C. Snelling, sec. ed., at pp. 20-21, 139-143 and 274-283.

Summary of the Invention

In general terms, the invention overcomes disadvantages of prior art structures by use of a core provided with an air gap which is both magnetically and physically shielded. Advantageous consequences of resulting partial gap devices include both reasonable fabrication cost and improved performance characteristics. Structures of the invention may profitably displace conventional full gap devices. As discussed under "Design Considerations", dimensions and other parameters may be optimized to retain inductance at high current and thereby to approach operating characteristics associated with full gap cores. Permitted uninterrupted surface contour at the joint avoids practical problems associated with the reduced cross-section of prior art partial gap joints.

The variable gap core which characterizes all structures of the invention, in fact, retains the performance advantages of earlier variable gap core structures as well. Accordingly, use may be made both of the high initial (zero current) inductance, characteristic of ungapped structures, and of the retained levels of inductance at high current, characteristic of gapped structures.

Joinder of core segments through surfaces together defining a region of peripheral contact to, in turn, enclose gapped region/s, overcomes art-recognized disadvantages of previously described non-linear core devices. Discussion is conveniently in terms of a single centrally located depression totally enclosed within a peripheral contacting region, thereby defining a centrosymmetric joint of the same external shape and dimensions as those of the core portions which are joined. A variety of considerations may dictate variations in location and shape of the resulting gap as well as use of multiple gaps.

The approach lessens - may totally avoid - fringing fields to, both, minimize heating through coupling with encircling windings and to improve performance efficiency via lessened eddy current loss and increased inductance. Alternatively, increased inductance-to-volume ratio may permit further miniaturization. Ordinarily attained viscosity values for, e.g., uncured crosslinking polymeric potting material, as dependent upon intimacy of peripheral contact, are sufficient to avoid entry into the gap, thereby preventing joint failure both in construction and during use. Exclusion may be further assured by bonding of contacting joint regions prior to potting.

Outlined characteristics are generally advantageous in a large family of conductively wound core devices. Inductance/current characteristics as well as joint stability are advantageous in a.c. apparatus - transformers and inductors. As with prior art non-linear core devices, a particular interest concerns energy storage inductors as well as chokes for d.c. apparatus such as power supplies. Implications include tolerance for apparatus design considered disadvantageous in the past. As an example, essential decoupling of closely spaced devices and leads, due to avoidance of fringing fields, permits free use of pancake windings of rectangular or oval cross-section, with implications including reduced volume and decrease in cost.

For expediency, discussion is in terms indicated - generally in terms of specific apparatus, e.g. inductors as used for choke coils - coils generally based on cores of a particular configuration, e.g. largely of circular cross-section, etc. The inventive advance is of broader value generally in the whole spectrum of "wire-wound" core devices. In all such instances, the inventive advances, in terms of magnetic and physical shielding, are valuable. By the same token, windings may be of any desired cross-section - constant or varying in size and/or shape.

Brief Description of the Drawing

FIG. 1, on logarithm coordinates of inductance and direct current, is a plot relating these properties for prior art (as well as for inventive) partial gap structures as compared with prototypical full gap and ungapped structures.

FIG. 2 is a cross-sectional view depicting an illustrative core structure designed in accordance with the inventive teachings.

FIG. 3, on coordinates of inductance index and ampere turns, is a plot relating those parameters for two similar structures - the first, that of curve 30, based on windings of round cross-section, the other, that of curve 31, based on windings of rectangular cross-section, both using the same core. Near coincidence of the two curves constitutes experimental evidence supporting substantial elimination of fringing fields.

FIG. 4, on coordinates of inductance and ampere-turns, is of design significance in showing performance characteristics of illustrative gapped, ungapped, and two partial gapped structures.

FIGS. 5A through 5F are perspective views of core segments of illustrative designs appropriate for use with the inventive teaching as mated with, e.g., planar mating surfaces not shown.

FIGS. 6A through 6D are cross-sectional views of unmated core surfaces to be joined with mating surfaces - e.g., with planar mating surfaces - and are representative of suitable configurations alternative to those of FIGS. 5A through 5F.

Detailed Description

Terminology

Description is for the most part in terms of included devices of particular interest at this time and using terminology familiar to present-day workers. The general thrust has been described: devices of the invention depend upon inductive coupling for current flow following a spiral conductor path encircling relevant region/s of a magnetic core. Devices of the invention have a feature in common - all entail a magnetic core which is continuous but for one or more partially gapped - partially contacting core joints. Consistent with general usage "continuous" may refer to: (1) physically continuous as, e.g. a toroidal core; (2) or mated core segments, often described as "ungapped", but in reality only approaching a toroid to the extent the mating surfaces are absolutely smooth. (For many purposes, "ungapped" refers to an effective gap of less than 0.5×10^{-3} in.) Such joints are variously described as "partial gap", "stepped gap" and "variable gap", and are responsible for "non-linear" structure (referring to a structure in which inductance manifests the form of dependence on current as that of curve 12 of FIG. 1).

By the same token, description, in familiar fashion, refers to "wire-wound". In common with general usage, use of this terminology contemplates devices, however made, which function in the manner of the prototypical core as literally encompassed by helical turns of wire. In fact, many "wire-wound" structures as presently manufactured, depend upon deposited or printed conductor segments, and not on literal "windings". It is likely that prevalent use of the invention will take the form of structures of this type. Terms such as "winding/s" and "coil/s" are to be so construed.

Design Considerations

To a significant extent, design considerations are well-known. Parameters of consequence - dimensions, compositions, etc. - at least in fundamental terms, are of the same impact as for earlier partial gap devices. An excellent reference, Soft Ferrites Properties and Applications, cited above at pp. 274-283, considers such designs for one category of devices - for choke coils and storage inductors. Similar considerations for other categories of devices are treated elsewhere in the same text. For this reason, detailed design is not considered a necessary part of this disclosure. Instead, discussion is in more general terms.

All structures of the invention have a feature in common - a core with a shielded gap. For this purpose, a shielded "gap" is defined as a core-enclosed three-dimensional discontinuity as produced by joinder of core surfaces, one or both of which are of topology to result in at least one such gap. To qualify as a "gap", it is required that retained inductance be at a function-consequential level for values of winding current beyond that characteristic of an ungapped structure otherwise of the same design parameters. For many purposes, this translates into a cross-sectional surface/surfaces defining a minimal gap of operational significance. Experimental work based on gap depth of a minimum of 0.5×10^{-3} in. assigns operational significance to a centrally located gap of area as small as 10% of that of the joint, and to a non-centrally located gap of lesser area - as small as 5% of that of the joint. This work was verified with mated RM10 cores with low profile. The RM10 core structure is defined by IEC Publication 431 - 1983 (Geneva, Switzerland) and JIS C 2516 - 1990 (Tokyo, Japan). The cores in this work were modified to have a height of 50% of standard, i.e. 0.183 in. per core half, as compared with 0.366 in. standard.

Gap depth can be related to incremental inductance and other parameters in accordance with the following equation:

$$L = \frac{\mu_o \cdot N^2 \cdot A}{\left[\frac{\ell}{\mu_\ell} + \frac{\delta}{\beta(\mu_m - 1) + 1}\right]}$$

where:

L = Inductance

N = Number of turns in the winding

A = Cross-sectional area of the magnetic circuit

ℓ = Magnetic path length of the body of the circuit excluding the gap region

β = Ratio of contact area at the gap region to the total Area A

μ_o = Permeability of air

μ_ℓ = Relative incremental permeability of the magnetic material in the body of the circuit

μ_m = Relative incremental permeability of the magnetic material in the region peripheral to the gap

δ = Gap depth

The relative permeabilities μ_ℓ and μ_m are non-linear functions of field strength - of the H fields, H_ℓ and H_m (relating to the fields in the body of the circuit, and in the region of the gap, respectively). The fields H_ℓ and H_m are, in turn, related to NI, the dc ampere turns, via the permeability dependent flux distribution between the gap and the contacting wall.

Accordingly, the equation cannot be solved analytically. Numerical methods such as finite element

analysis, may be used to obtain solutions with reasonable accuracy. Nevertheless, this equation, in conjunction with approximations for values of μ_ℓ and μ_m, may serve as a useful starting point for empirical investigation of the variation in, L, as dependent on values of δ, β, and I_{dc}.

Chosen dimensions are with a view to device function. Where the desire is operation approaching that of a full gap structure. peripheral wall thickness is minimized. In such instance, the primary purpose of the retained contacting regions of the final core joint is avoidance of fringing fields and physical joint integrity. A wall thickness of 10^{-2} in. is functionally sufficient for field shielding. Minimum wall thickness to avoid mechanical failure is largely a matter of physical stability and fabrication expedience. Experimentally, ferrite of 10^{-2} in. wall thickness has been found adequate for structures studied.

In instances in which the device is to function in the manner of some earlier partial gap devices, e.g., in instances in which high values of inductance at low current operation are of particular consequence, peripheral wall thickness is likely greater than the minimum values considered in the previous paragraph. Retained inductance at high current is, in such instances, as shown in FIG. 1, is somewhat reduced. However, a centrally located gap of area as small as 38% of the total cross-sectional area of joinder results in a functionally significant increase in retained inductance at increased current for structures studied and, accordingly, qualifies for use in contemplated devices. For studied low profile core devices, e.g. for RM10 design as referenced above, such a minimal gap area, with gap depth of 19×10^{-3} in. results in device-significant inductance at currents approximately four times greater than for the corresponding ungapped structure (plateau values corresponding with region 19 of FIG. 1).

While starting design parameters are generally calculable, realistic considerations require some trial and error. For example, deviation from perfect surface smoothness may require some empiricism (e.g., compare curve 10 of FIG. 1 with curve 40 of FIG. 4, the first relating inductance to current for a true ungapped core and the second based on related properties for a real structure including joinder of two "smooth" surfaces). It may even be that with experience gained, design of new structures may dispense with theoretical considerations altogether.

Included structures are of greatest advantage for closely spaced, low profile, small-dimensioned devices where temperature rise is of particular consequence. From this standpoint, device dimensions of a fraction of an inch and as similarly spaced, in particular, gain from avoidance of heating due to fringing field coupling.

Fabrication

Considerations under this heading are again well-understood for devices meeting present requirements. Core composition requirements are somewhat eased in view of the inventive attribute of increased inductance per unit volume, particularly with rectangular or oval cross-section windings. Structures for inclusion in usual wiring board circuitry may make use of familiar ferrite compositions, e.g. of manganese-zinc or nickel-zinc based ferrites. Required magnetic characteristics and fabrication requirements may result in any of a variety of alternatives - e.g., elemental metals and alloys, as well as other ferrites. Recent advances in the construction of a major category of such structures may be of benefit. U.S. application, serial no. 07/710,736, filed May 31, 1991, describes a relevant core structure fabricated from core segments through adhesive joinder. It has been noted that coil windings are likely to take form other than that of literal wire-woundings. U.S. application, serial no. 07/835,793, filed February 14, 1992, describes joinder of partial turns to result in functioning windings. Other fabrication approaches, some in commercial use, others described in the literature, may serve.

The Figures

FIG. 1 has been considered in earlier discussion. The three curve forms presented, those of curves 10, 11 and 12, are representative of the general form of inductance v. d.c. current, L v. $I_{d.c.}$, as plotted on log-log coordinates. These curves correspond with ungapped and partial gap core structures, respectively. For discussion purposes, axis-intercept values are treated as zero values of the other coordinate axis even though only approaching such values since on logarithmic coordinates. The ultimate values of inductance at 14, 16 and 20, however approach, the non-zero values as obtainable from the air core device to which the structure under study is effectively converted upon magnetic saturation of the core. The value of $I_{d.c.}$, at which value 14 is attained varies - i.e. the severity of the fall-off of curve 10, for an otherwise similar structure including joinder of less-than-perfect "smooth" mating surfaces decreases as surface imperfections increase.

Curve 11, depicting the relationship of inductance and current for a full-gap structure, commences at initial inductance 17 for zero current, maintains constant or plateau value for the major part of the curve for region 15, and finally drops off to attain minimal inductance value 16. The plateau value as well as the fall-off position varies with changing gap. Increasing the size of the gap results in a decrease in inductance together with an increase in the value of current at fall-off. Again, the relationship is known - a useful reference is the tex Soft Ferrites cited above (see,

Figure 9.13, p. 277 and related text).

Curve 12, representative of partial gapped structures, commences at zero current value of inductance at 18, thereafter falling off to plateau value 19, and ultimately to small inductance (air core value) at 20. As discussed, the form of the relationship as represented by curve 12 may be made to more closely approach curve 10 or 11. Briefly, relative increase of contacting surface at joinder (of ratio, β = contact area/total area) as well as decrease of gap depth produces a characteristic relationship more closely approaching of the ungapped structure of curve 10. The actual zero current inductance value is mainly dependent on β. The inverse, e.g. reduction in β, results in characteristics approaching the form of curve 11, e.g., in that region before its intercept with curve 10. The magnitude of inductance at plateau value, 19, decreases, and the current value at fall-off, 20 increases with gap depth, δ.

FIG. 2 is a perspective view in cross-section of a mated E core structure 21 similar in cross-section to that used in experiments upon which much of the reported data was measured. It, in turn, consists of mating segments 22 and 23, together defining gap 24, in this instance, the consequence of joinder of recessed surface 26 and planar surface 27. In common with other contemplated structures, gap 24 is enclosed within core material, thereby forming wall 25 about its entire periphery, including the face portion of structure 21 removed in draft-sectioning.

FIG. 3 contains plotted information for two partial gapped structures providing for substantial elimination of fringing fields. Coordinates are inductance index, AL = L/N^2 on the ordinate, (in which L is inductance in nanohenrys and N is number of turns) and ampere-turns, NI on the abscissa. The two experimental structures used the same cores, the first, that of curve 30, having a 26-turn spiral winding of round cross-section conductor, the second having a 3-turn helical (pancake) winding of rectangular cross-section conductor. Substantial coincidence of curves 30 and 31 is clear evidence of absence of fringing fields since such fields would couple more strongly with pancake windings (as carrying current to result in the same number of ampere turns), thereby resulting in a lowered plateau value for that structure - for the structure of curve 31.

FIG. 4 is a log-log plot of inductance, L in microhenrys, on the ordinate, and of ampere-turns, NI, on the abscissa, for four low profile RM10 (FIG. 5C) core structures, all of similar design but for gap presence and dimensions. Curve 40 relates these quantities for an ungapped structure, curve 41 is for a full gap of 20 x 10^{-3} in. depth, curve 42 reports measurements for a 20 x 10^{-3} in. depth cylindrical gap encompassed by a 40 x 10^{-3} in. wall, curve 43 is for a structure similar to that of curve 42 but of 31 x 10^{-3} in. wall thickness. As discussed, characteristics of the ungapped structure of curve 40 are more closely approached as relative contact area increases, while full gap is more closely approached with decreasing area.

FIGS. 5A through 5F are perspective views of core loop segments presently in use. As before, shown segment surfaces may be mated with contoured surfaced segments, e.g. with mirror image segments, or alternatively, with planar (or ungapped) surface segments. Depicted structures, as well as a large number of alternatives, are described in detail in Soft Ferrites, cited above. Views correspond with structures as follows: 5A - U core, 5B - E core, 5C - RM core, 5D - low profile core, 5E - EP core, and 5F - pot core. As depicted, all structures shown are provided with a depression illustratively centrally located and of the cross-sectional shape of the containing core leg.

FIGS. 6A through 6D are perspective views in section of core segments representative of a much larger number of gap configurations, any of which may be joined with segments having contoured or with planar mating surfaces.

FIG. 6A depicts a multiple cavity gap - in this instance containing cavities 60 and 61 within unrecessed portion, or wall, 62.

FIG. 6B depends upon a stepped gap 63 consisting of gap regions 64 and 65, defined by wall 66.

FIG. 6C illustrates a structure providing for a gap 67 of varying depth as enclosed within wall 68. FIG. 6D depicts a structure dependent on an annular gap 67 enclosed within wall 68 and, in turn, enclosing unrecessed region 69.

Examples

Example 1

Three choke coils of the same shape, size, composition and number of winding turns were energized to result in data of the form depicted in FIG. 1. The cores used in all three, were low profile RM10 cores - as depicted in FIG. 5C, mated with an ungapped core-half, and were provided with a 26 turn winding encircling the center leg. The size of each mated core pair was approximately 1.09 in. x 0.52 in. x 0.37 in. with a round center leg of diameter 0.42 in. The first structure was ungapped, the second was gapped with constant depth of 20 x 10^{-3} in. in the center leg and the third was provided with a shielded cylindrical gap of 19 x 10^{-3} in. depth encircled by a peripheral wall of 34x 10^{-3} in. thickness as depicted. As energized, measured inductance value was as plotted on FIG. 1 with zero current inductance of 4470, 174 and 2360 microhenrys and with low inductance (70 μH corresponding with points 14, 16 and 20) at $I_{d.c.}$ = 0.9 amp., 7.0 amp. and 5.5 amp., respectively. A note in passing - both the curve form and values reported were approximately the same for a prior art partial

gap structure (of peripheral rather than enclosed gap).

Example 2

Two flyback transformers, the first fully gapped, the second of enclosed partial gap (wound core of round 0.416 in. diameter cross-section, of gap depth $= 20 \times 10^{-3}$ in. and $\beta = 0.27$) otherwise of the same size (low profile RM 10), core composition, primary and secondary coil structure, were activated in a flyback converter circuit to determine performance differences. Both were operated at average input current of approximately 2 amperes as resulting from input at 500 kHz, 40 volt. The transformer with the enclosed partial gap showed a transformer loss of 3 watt, about 20% lower than that with the full gap, while maintaining converter performance in all other respects.

Example 3

Measured data curves as shown on FIG. 3 were based on two structures of the same shape, size and composition as that of the partial gap structure of Example 1. The core used was gapped to a depth of 20×10^{-3} in. The gap diameter was 0.354 in. and was enclosed by a 31×10^{-3} in. wall (to result in $\beta = 0.28$). The coil in the first structure consisted of 26 turns of 17.9×10^{-3} in. diameter, round cross-section copper wire. The second was provided with three turns of 0.150 in. x 20×10^{-3} in. rectangular cross-section ("pancake") conductors with the long dimension radially disposed relative to the core. As recorded on FIG. 3, both curves plateaued at a value of inductance index, AL, of 200-300 nanohenrys per turn-squared over the range of from 6-100+ ampere-turns. As shown in that figure, inductance index was near-identical so supporting assumed avoidance of fringing field. (More intimate coupling of fringing field with the pancake windings would have resulted in less effective operation to lessen inductance.)

Example 4

Four cores of the same shape, composition and dimensions, all provided with a twenty-six turn winding were operated at 500 millivolt and at a frequency of 100 kilohertz to result in the inductance characteristics reported on FIG. 4. The first, ungapped, resulted in the measured values of curve 40. A fully gapped structure - of 20×10^{-3} in. constant gap depth - produced the characteristics plotted as curve 41. Two partial gapped structures resulted in the performance of curves 42 and 43. The purpose of the experiment was to verify the effect of varying β (the ratio of contacting to total surface at the joint, and, accordingly, only the diameter of the gap varied as between the two). The structure corresponding with curve 42 was provided with a cylindrical gap of 20×10^{-3} in. depth as enclosed within a 40×10^{-3} in. wall for a value of $\beta = 0.35$. The second partial gap structure, on which data points for curve 43 was measured, differed only in increased gap diameter to leave a wall thickness of 31×10^{-3} in.($\beta = 0.28$). It is seen that increased β resulted in a partial gap structure more nearly approaching that of the ungapped structure with regard to inductance at lower current values. Decreased β resulted in inductance/ampere-turn ratio more closely approaching that of the full gap structure.

Claims

1. Apparatus comprising a magnetic core defining at least one substantially continuous magnetic path, said core provided with at least a first set of windings defining an electrical current path about said core, thereby yielding a coil, said magnetic path including a partial gap of reduced magnetic permeability and increased saturation magnetic flux density, whereby such apparatus has operating characteristics intermediate those resulting from use of a full gapped and an ungapped core, CHARACTERISED IN THAT such partial gap comprises substantially a gap which is totally enclosed within the core so as to provide physical and magnetic shielding for the gap whereby magnetic fringing fields produced in operation are substantially unchanged by the gap.

2. Apparatus of claim 1 in which the relative magnetic permeability of such path is numerically greater than 1.

3. Apparatus of claim 2 in which the relative magnetic permeability is greater than 2.

4. Apparatus of claim 3 in which the core includes but one such, said gap consisting essentially of a void resulting from joinder of core surfaces, at least one of which includes a depression, such surfaces being provided with peripheral regions to result in total enclosure of such gap and magnetic path continuity.

5. Apparatus of claim 4 in which such gap is centrosymmetrically located.

6. Apparatus of claim 5 in which such gap is of cross-sectional shape approximating that of the core in the region of the gap.

7. Apparatus of claim 6 in which such gap is of varying depth.

8. Apparatus of claim 4 in which the total gapped area is of a maximum value of 95 area percent of the total core cross-section in the region of the gap.

9. Apparatus of claim 8 in which gap depth is at least $0.5x10^{-3}$ in. for a gap area of 5% of such area percent.

10. Apparatus of claim 4 in which at least the region including the said gap is potted and in which potting material is excluded from the gap by such peripheral regions.

11. Apparatus of claim 10 in which potting entails immersion in potting fluid, and in which the viscosity of such fluid is sufficiently high so that the periphery of the joint is substantially unpermeated.

12. Apparatus of claim 11 in which such potting fluid consists essentially of an organic polymeric material which becomes cured to increase its viscosity following immersion.

13. Apparatus of claim 1 in which said core and coil function as an inductor.

14. Apparatus of claim 1 including at least two coils about such core functioning as a transformer.

FIG. 1

(PRIOR ART)

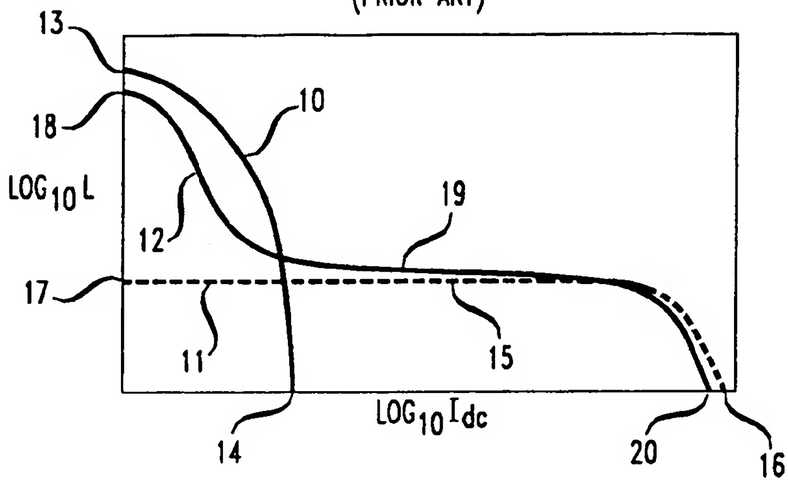


FIG. 2

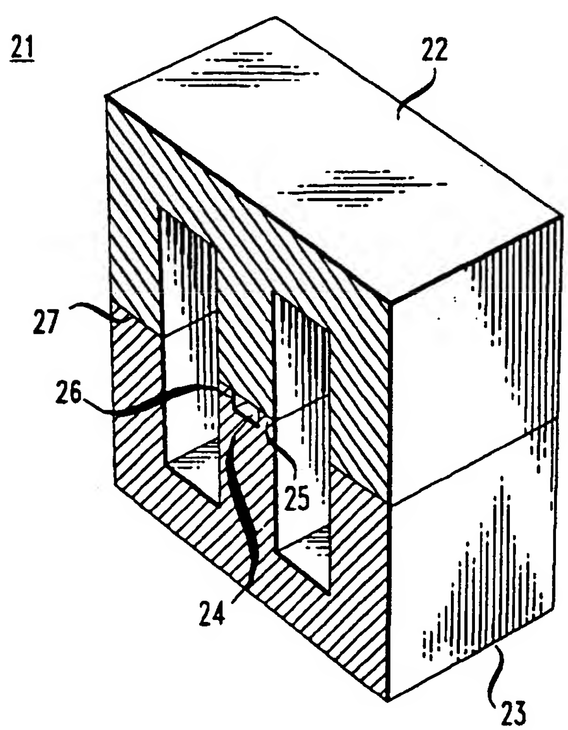


FIG. 3

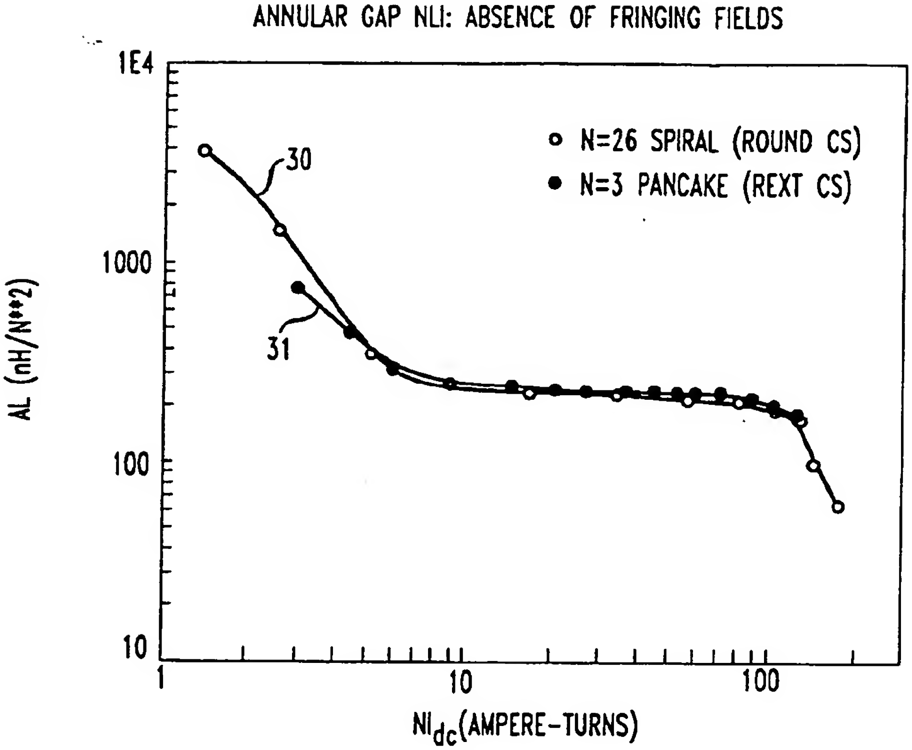

ANNULAR GAP NLI: ABSENCE OF FRINGING FIELDS
N=26 SPIRAL (ROUND CS)
N=3 PANCAKE (REXT CS)
30
31
1E4
1000
100
10
1
10
100
AL (nH/N**2)
NI_{dc}(AMPERE-TURNS)

FIG. 4

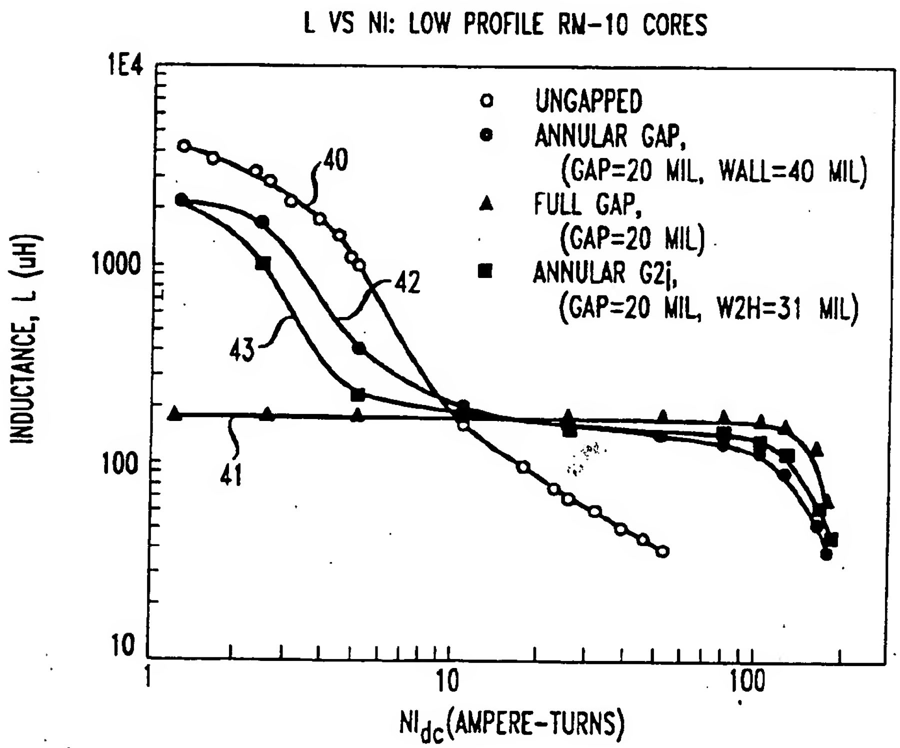

L VS NI: LOW PROFILE RM-10 CORES
UNGAPPED
ANNULAR GAP,
(GAP=20 MIL, WALL=40 MIL)
FULL GAP,
(GAP=20 MIL)
ANNULAR G2j,
(GAP=20 MIL, W2H=31 MIL)
40
42
43
41
1E4
1000
100
10
1
10
100
INDUCTANCE, L (uH)
NI_{dc}(AMPERE-TURNS)

FIG. 5A

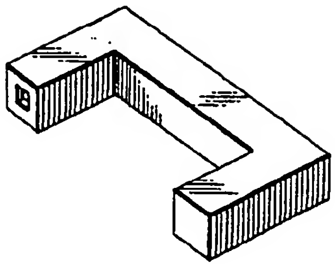


FIG. 5B

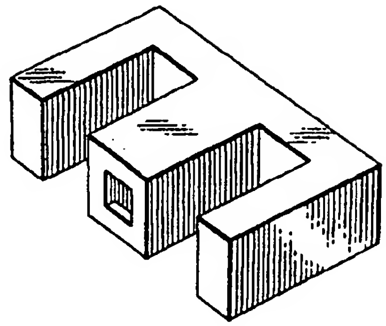


FIG. 5C

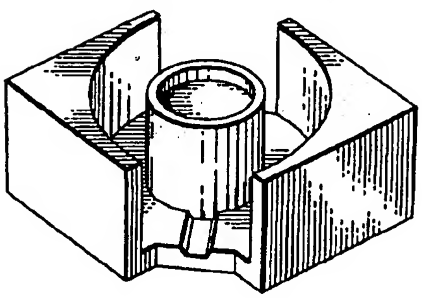


FIG. 5D

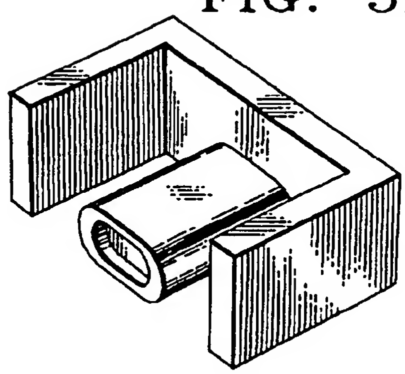


FIG. 5E

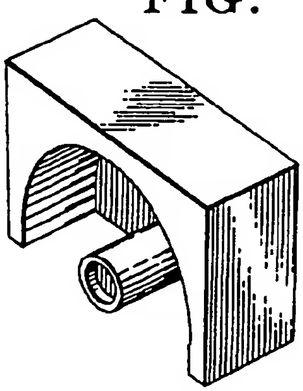


FIG. 5F

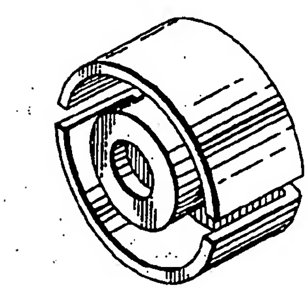


FIG. 6A

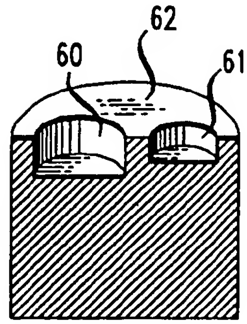


FIG. 6B

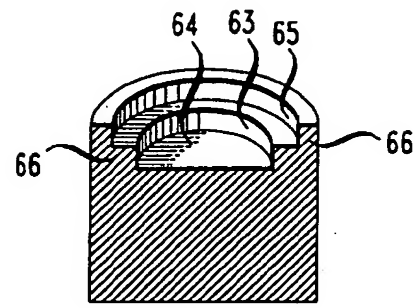


FIG. 6C

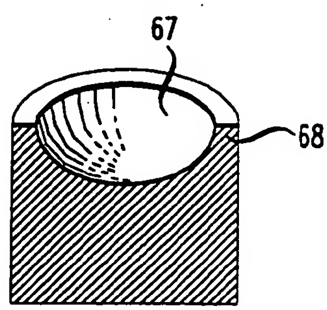
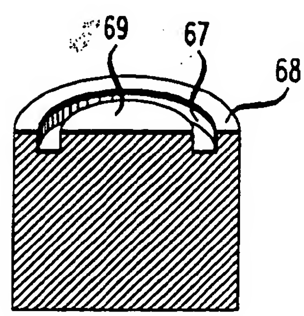


FIG. 6D



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(71) Applicant: **AMERICAN TELEPHONE AND TELEGRAPH COMPANY**
32 Avenue of the Americas
New York, NY 10013-2412 (US)

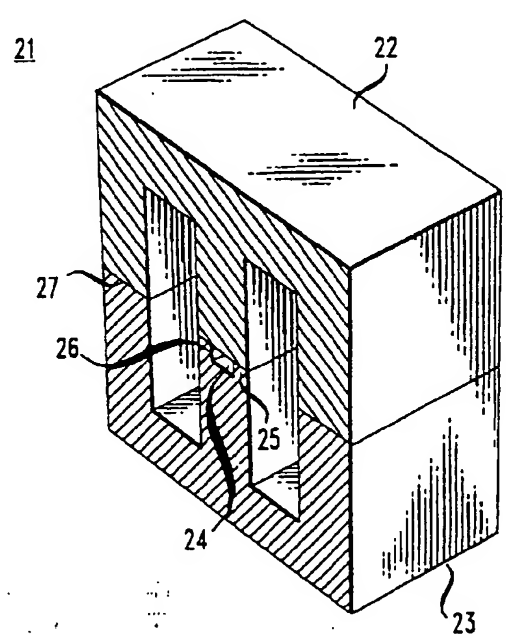
(72) Inventor: **Roy, Apurba**
1602 Amesbury Avenue
Rockwall, Texas 75087 (US)

(74) Representative: **Johnston, Kenneth Graham et al**
AT & T (UK) Ltd. 5 Mornington Road
Woodford Green Essex, IG8 OTU (GB)

(54) **Partial gap magnetic core apparatus.**

(57) Potted wire-wound loop-core structures are based on cores which include partial gapped inductors or transformers with their reduced dependence of inductance on current during operation. Total enclosure of gaps by encircling core material is both magnetic and physical, thereby avoiding fringing magnetic fields as well as joint failure due to differential expansion of potting material.

FIG. 2



EP 0 577 334 A3

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 93 30 4935

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.5)
X	US-A-3 793 557 (BERKEY-COLORTRAN) * column 6, line 20 - line 54; figures 6-8 *	1	H01F3/14 H01F37/02 H01F27/34
X	DE-A-26 58 456 (LICENTIA) * page 4, paragraph 2 -paragraph 4 *	1	
X	DE-A-36 22 190 (PHILIPS PATENTVERWALTUNG) * column 2, line 59 - column 3, line 21 *	1	
A	US-A-4 047 138 (GENERAL ELECTRIC COMPANY)		
A	DE-C-922 423 (A.E.G.)		
A	DE-A-27 01 558 (VOGT GMBH & CO)		
A	US-A-1 876 451 (TELEFUNKEN)		
			TECHNICAL FIELDS SEARCHED (Int.Cl.5)
			H01F

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	17 December 1993	Vanhulle, R

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